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Influence of voids and pockets on vibration characteristics of railway concrete sleepers

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ABSTRACT: Railway prestressed concrete sleeper or so-called "concrete tie" is an important component of railway track structures. The dynamic interaction between concrete sleepers and ballast bed has rarely been studied because of the main emphasis placed on global track dynamics. Until recently, the health monitoring of track components becomes compulsory in order to develop the optimal maintenance model. Since railway tracks are normally subjected to dynamic loading, it is crucial therefore to evaluate the dynamic properties of their components. Experimental modal analysis is an efficient technique to evaluate the mechanical properties of any structures based on the non-destructive testing measurements.

This paper presents results of an experimental modal analysis of prestressed concrete sleepers in voided in-situ conditions. Two types of prestressed concrete sleepers were provided by the Australian manufacturers. The concrete sleepers were tested using an impact hammer excitation technique over the frequency range of interest: 0 to 1600 Hz. Frequency response functions (FRFs) were measured using the Bruel&Kjaer PULSE dynamic analyser. The FRFs were processed using the STARModal analysis package to identify natural frequencies and the corresponding mode shapes for the sleepers. The conclusions are presented on the effect of voids and pockets on the dynamic properties of prestressed concrete sleepers. The void configuration presented is the single hovering. Vibration parameters of concrete sleepers are required for the development of a realistic dynamic model of railway track capable of predicting its responses to impact loads due to wheel burns, irregularities of the rail, so on.

1. INTRODUCTION

Ballasted railway track has become very common in rolling stock transportation and freight, especially in Australian coal and mining businesses. The Australian railway industry paid approximately 25–35 percent of its annual budget on rail track maintenance. The replacement costs of rails and sleepers were a considerable part of the expense [1]. Two major parts of ballasted railway track are the super-structure and the sub-structure. The super-structure is made up of steel rails, the fastening systems and sleepers; whilst the ballast, sub-ballast, sub-grade and formation, form the sub-structure. Figure 1 illustrates the ballasted track components. Esveld [2] notes that ballasted track has many advantages; for example, the construction costs are comparatively low, the maintenance and repair of track and its components are convenient, it has high damping and very good drainage properties, and noise can be controlled. Since railway track is always subjected to a variety of time-dependent loads, understanding the dynamic track behaviour is essential in order to evaluate the structural safety and service life of the railway track components.

Typically, sleepers are the track components resting on the ballast formation transversely as shown in Figure 1. Railway sleepers were first made in timber, and then a limited number of steel sleepers were used, followed by the now most-popular concrete sleepers. The majority of modern railway sleepers used worldwide are the prestressed concrete sleepers. In general, functions of the sleepers are to:

- support and restrain the rail foot;
- sustain and distribute loads from the rail foot to the underlying ballast;
- maintain the rail gauge and shape, and preclude rail inclination and track instability;
- withstand longitudinal, lateral and vertical rail movements;
- provide insulation between parallel rails, and
- resist wearing and loading, and endure extreme weather conditions from cold to hot, and from rain to drought.

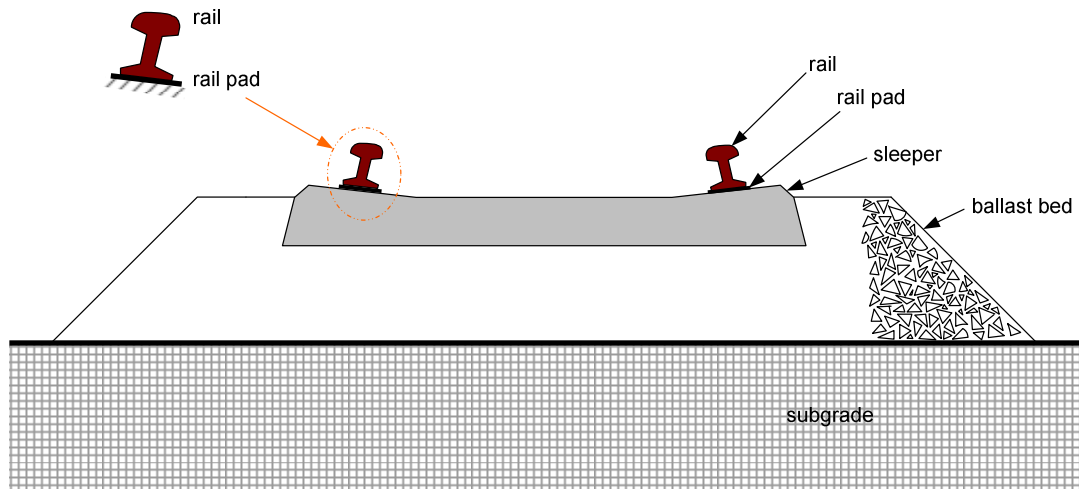


Figure 1 Typical ballasted track structure

There are two commercially available types of concrete sleepers: twin-block and monoblock sleepers, as shown in Figure 2. The former sleepers were originally developed in France and used in Europe, India, Brazil, and Mexico. The later ones first came from the UK and have been adopted in countries such as Australia, Canada, China, Japan, the UK, the USA, and the former USSR [3]. Due to the nature of dynamic loadings on railway track, the vibration characteristics of concrete sleepers are essential in analysis and design procedures. Also, to develop and validate a numerical simulation of rail track, the free vibration characteristics of the sleepers in various conditions are needed. Archives of vibration response measurements and parameters of sleepers can help engineers to identify the vibration-based damage or remotely monitor the sleeper health, since it is clear that the sleeper damage occurs mostly at resonant frequencies of the sleepers [4]. The resonant vibrations of sleepers affect not only the sleepers themselves, but also the wheel-rail interaction forces. These effects have been analytically studied by Clark et al. [5], Grassie and Cox [6], and Knothe and Grassie [7]. Due to their wide use, the design and maintenance of prestressed concrete sleepers is a major concern to Australian track engineers.

There have been a number of studies related to the evaluation of dynamic properties of concrete sleepers. Experimental modal analysis is one of the widely used techniques to determine the vibration characteristics of concrete sleepers. Ford [8] performed modal analysis on a concrete sleeper in free-free condition using an electrodynamic shaker. Dahlberg and Nielsen [9] developed an analytical model for analysing dynamic behaviour of concrete sleepers in both free-free and in-situ conditions. Based on the experimental results, a two-dimensional dynamic modelling for vibration analysis of concrete sleepers was done by Grassie [4]. It was found that the Timoshenko beam element was the best approximation of the concrete sleepers, even though the elastic properties of prestressed concrete sleepers may not be precise. Recently, Gustavson [10] and Vincent [11] performed the three-dimensional finite element modelling and modal testing of concrete sleepers in free-free condition. The results were in good agreement between numerical and experimental data. In reality, however, the sleepers are placed on ballast/subgrade formation. A comprehensive sleeper-ballast dynamic interaction has rarely been studied. Recently, the studies on rail pad parameters, improper ballast tamping, and the dynamic interaction between ballast and sleeper have been investigated [12-14]. However, the effect on imperfection of ballast and sleeper contact has yet been presented elsewhere.

This paper presents results of an experimental modal analysis of prestressed concrete sleepers in the voided in-situ conditions. Full-scale prestressed concrete sleepers were provided by the Australian manufacturers. Impact hammer excitation technique has been used to evaluate the modal data over the frequency range of interest: 0 to 1600 Hz. Frequency response functions (FRFs) were obtained using the Bruel&Kjaer PULSE dynamic analyser. The FRFs were processed using the STAR Modal analysis package to identify natural frequencies and the corresponding mode shapes for the sleepers under the particular conditions. The conclusion highlights the effect of voids and pockets on the dynamic properties of prestressed concrete sleepers.

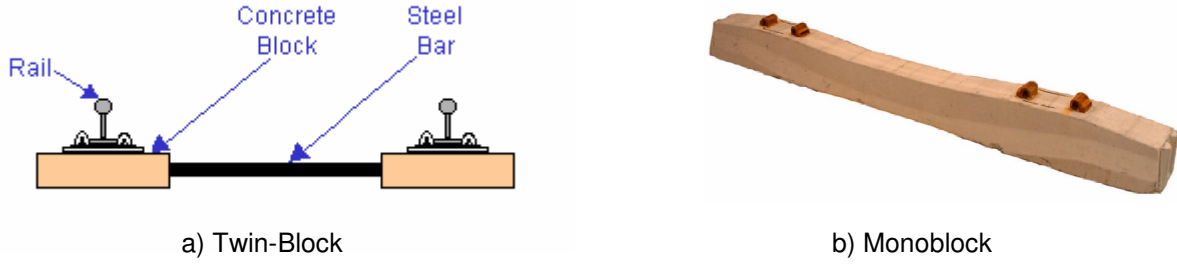


Figure 2 Concrete sleepers

2. MODAL ANALYSIS

Measurements of vibration responses in structures result in the modal parameter identification to obtain the dynamic characteristics of the structures. There are a number of methods to extract the dynamic characteristics, depending on the format of data obtained [15-16].

In a dynamic system, the equation of motion of the system can usually be represented by

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{f\} \quad (1)$$

where $[M]$ is the mass matrix, $[C]$ is the damping matrix, and $[K]$ is the stiffness matrix. The harmonic force applied to the system with magnitude F and loading frequency ω is given by

$$\{f\} = F \sin \omega t = F e^{j\omega t} \quad (2)$$

The analytical solution can be contrived by Fourier Transform and can be found in [12].

3. MODAL TESTING

All test specimens were prestressed concrete sleepers designed in accordance with AS1085.14-2003 [17]. The dimensions and masses of the test sleepers are tabulated in Table 1. Sleeper No. 1 is the heavy-duty sleeper provided by ROCLA. Sleeper No.2 is the narrow-gauge sleeper provided by AUSTRAK. The excitation points were located on the top surface of the sleeper at every 150 mm along the perimeter. Based on previous experience, it was found that the number of these positions is ample to represent the vibration modes of interest. In this case, an accelerometer had a fixed position whilst an instrumented impact hammer was roved along the excitation points. Figure 3 shows the experimental setup of a sleeper on full-contact ballast bed. After performing the modal testing, the voids were then constructed on the ballast bed that imitated the void problem in railway tracks, as illustrated in Figure 4a. Also, it is found that the best position for mounting the accelerometer is at the end of the sleeper. The instruments used in this study were a PCB accelerometer, the PCB impact hammer, and the Bruel&Kjaer PULSE vibration analyser. The accelerometer was mounted at the sleeper end. Using the hammer to excite vibrations in the sleeper over the frequency range 0 to 1,600 Hz, the 10-time average vibration responses represented by the FRFs were obtained using the PULSE system. Then, processing the recorded FRFs by STARModal gave the natural frequencies and modal damping constants of the sleeper. All procedures were performed twice per an amount of voids underneath the sleepers. The modal testing was performed on each particular amount of voids by degrees.

Table 1 Dimensions and masses of the test sleepers

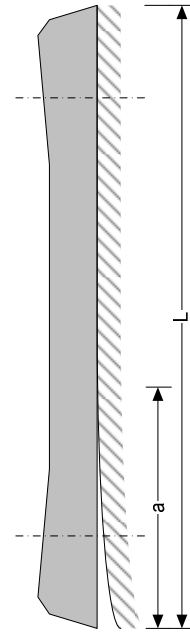
Sleeper No.	Mass (kg)	Total length (m)	At railseat (m)		At centre (m)	
			width	depth	width	depth
1	206.0	2.50	0.20	0.23	0.21	0.18
2	283.0	2.15	0.18	0.25	0.16	0.24



Figure 3 Full contact between ballast and sleeper



a) experimental setup



b) schematic contact configuration

Figure 4 Partial contact between ballast and sleeper

Figure 4b presents the contact pattern in this study, which is referred to as 'single hovering'. In this type, there is a hovering arising at one end of the sleeper. The hovering space incrementally grows from perfectly full contact to totally hung conditions. This void may be extended either from any end since the traditional sleepers are symmetrical so that the dynamic effect remains similar. Non-dimensional variables related to the ratio of single-side void length to sleeper length to be noted in this case are as follows.

$$\alpha_s = \frac{a}{L} \quad (3)$$

Table 2 Modal parameters of Sleeper No 1 with different single hovering conditions

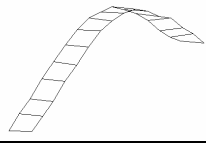
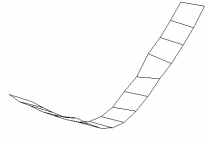
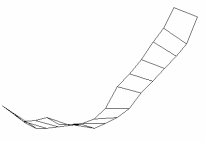
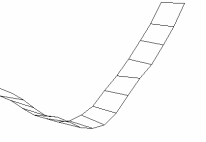
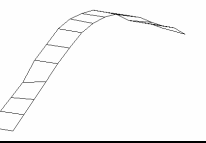
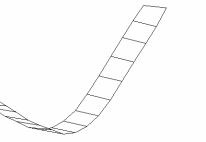
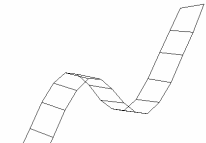
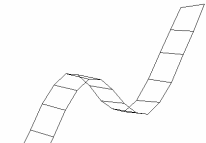
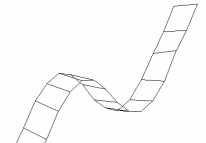
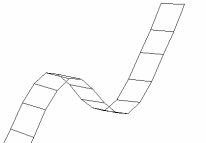
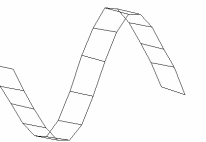
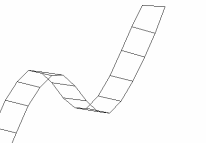







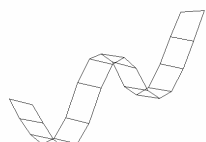
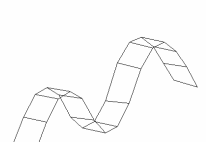
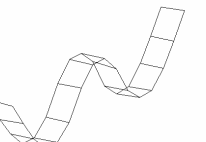
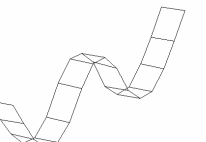
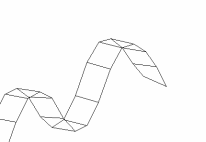
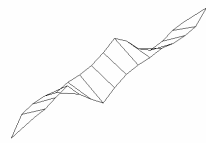
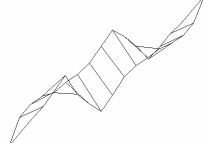
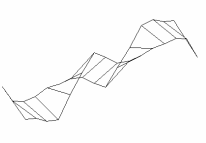
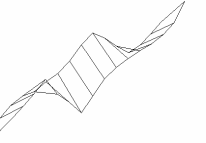
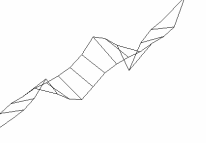

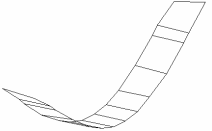
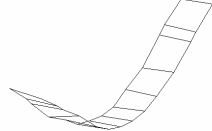
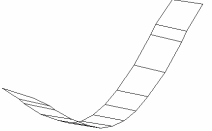
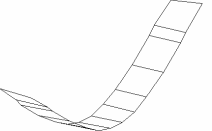
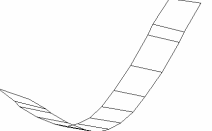
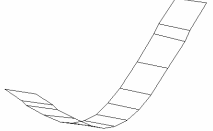
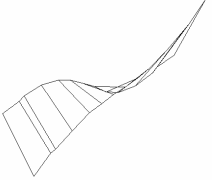
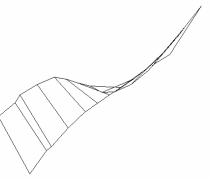
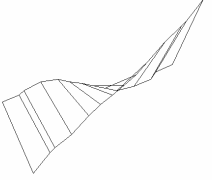

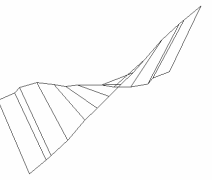
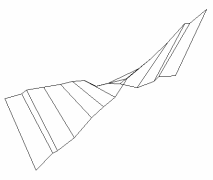
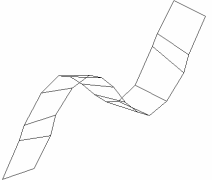
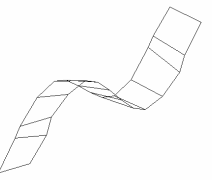
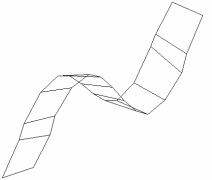
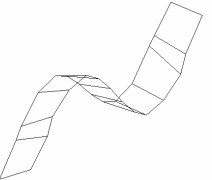
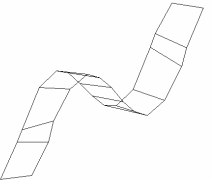
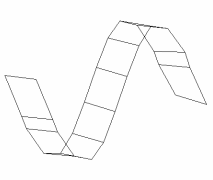
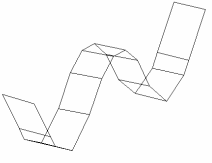
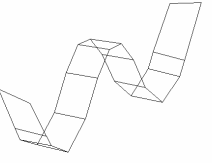
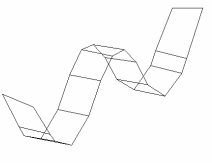
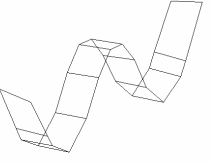
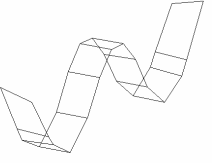
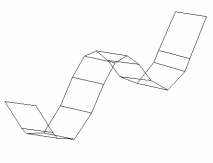
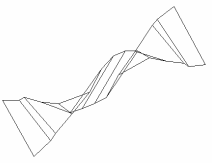
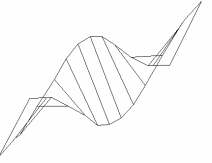
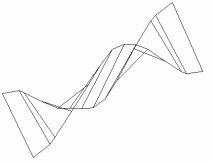
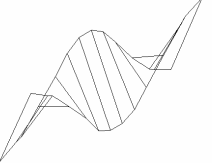
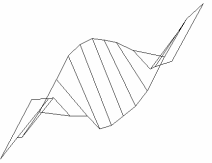
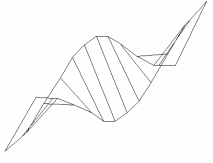
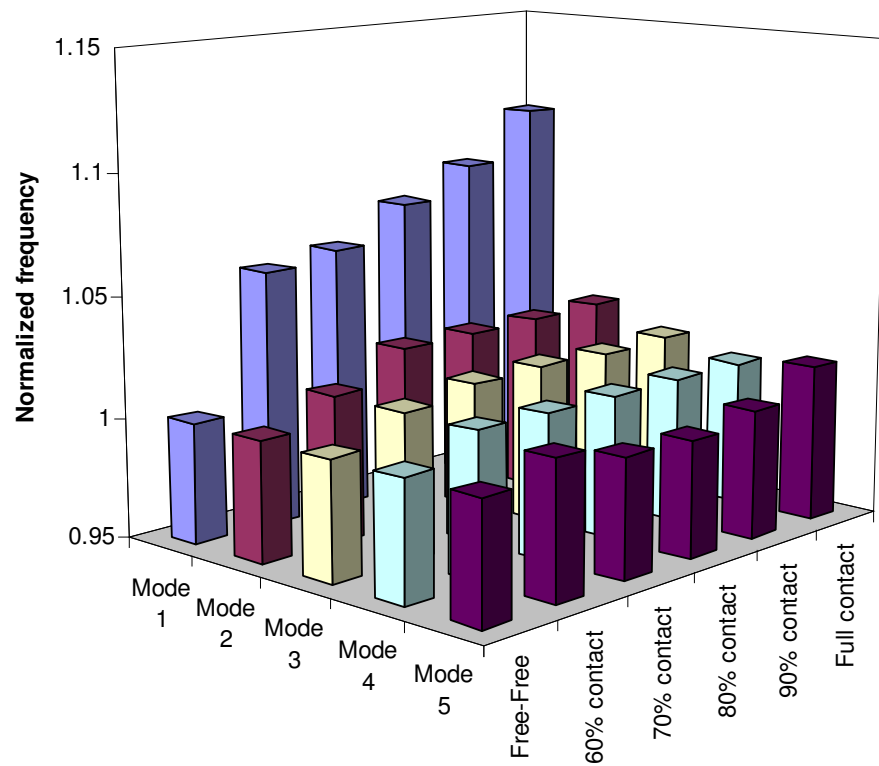
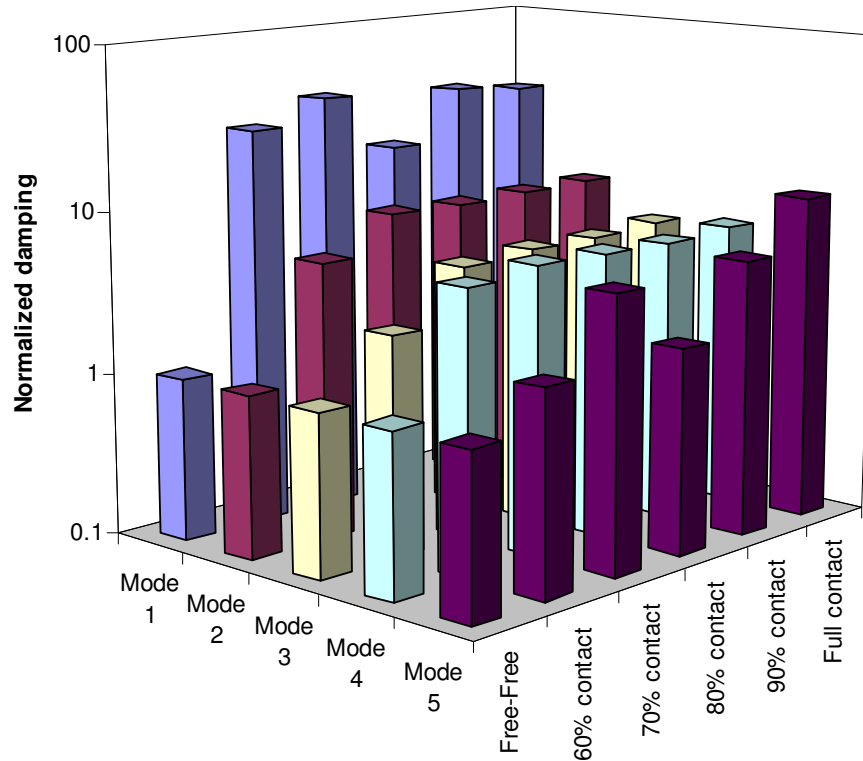
Mode	Full Contact		90% Contact		80% Contact		70% Contact		60% Contact		Free-Free	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1												
	150.39	8.460	147.61	9.338	145.92	4.435	143.93	10.38	143.34	7.485	135.71	266.37m
2												
	414.93	2.586	414.64	2.531	414.57	2.472	414.49	2.546	409.37	1.517	404.83	298.96m
3												
	489.18	1.763	488.63	1.666	489.12	1.677	488.85	1.575	486.63	747.434m	481.36	331.86m
4												
	775.56	1.624	775.61	1.528	775.40	1.577	775.61	1.644	775.98	1.450	767.84	279.37m
5												
	1,172.51	3.015	1,159.37	1.471	1,153.67	535.525m	1,155.05	1.411	1,163.67	502.645m	1,155.31	292.75m

Table 3 Modal parameters of Sleeper No 2 with different single hovering conditions

Mode	Full Contact		90% Contact		80% Contact		70% Contact		60% Contact		Free-Free	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1												
	237.14	5.519	237.12	6.437	236.19	6.052	234.06	4.960	232.03	5.420	223.09	216.74m
2												
	562.64	917.119m	562.52	871.444m	562.20	1.051	561.78	553.555m	561.44	246.879m	561.62	173.17m
3												
	600.55	2.048	600.46	2.231	600.19	2.021	599.36	1.500	595.29	712.900m	593.19	209.72m
4												
	1,098.51	862.564m	1,097.16	795.925m	1,096.85	704.513m	1,096.30	596.048m	1,095.89	466.479m	1,092.68	236.33m
5												
	1,272.21	1.114	1,268.50	1.123	1,268.45	921.890m	1,269.47	903.429m	1,270.32	823.757m	1,266.67	242.36m

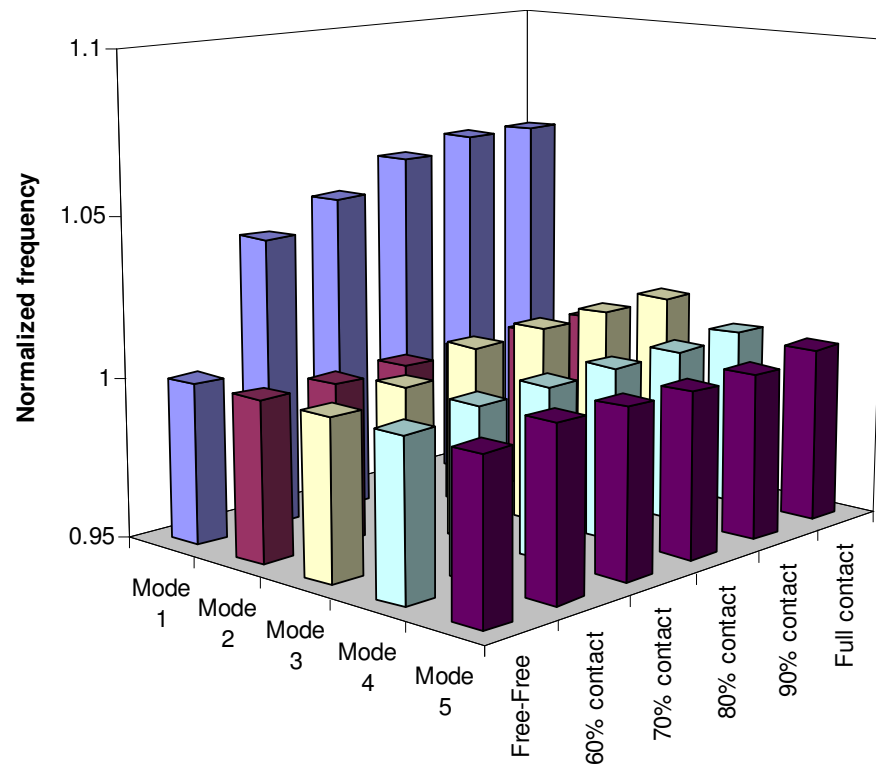


a) modal frequency

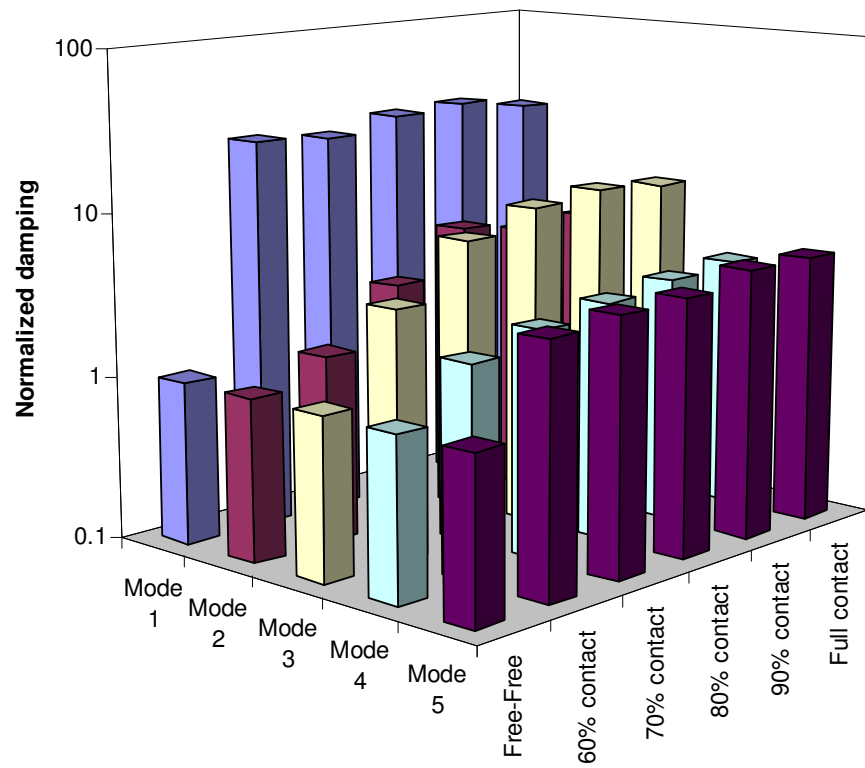


b) modal damping

Figure 5 Normalized modal data of Sleeper No 1



a) modal frequency



b) modal damping

Figure 6 Normalized modal data of Sleeper No 2

4. RESULTS

The results of modal testing for Sleepers No. 1–2 are illustrated in Tables 2–3, respectively. In these tables, the first five modes of vibration are presented. For all sleepers, it was found that the first bending mode in a vertical plane clearly dominated the first resonant mode of vibration in either free-free or void conditions. Table 2 shows the experimental dynamic properties of Sleeper No. 1 (ROCLA Heavy Duty). For a free-free condition, the lowest frequency associated with the fundamental bending mode, the second frequency with the second bending mode, the third frequency with the lowest torsional mode, the fourth frequency with the third bending mode, and the fifth mode with the second torsional mode. Similar modes of vibration were identified for the sleeper in the voided sleeper conditions. Of all five modes, the most significant change in natural frequencies between the free-free and in-situ conditions was the first bending mode. The maximum frequency increase was about 15 percent. However, it was found that at higher resonant frequencies, the effect of boundary conditions was remarkably decreased to only two percent difference in the forth and fifth vibration modes. Also, it should be noted that the ballast support played a significant role in increasing the damping values of all vibration modes. The maximum damping increase due to sleeper-ballast interaction was more than 50-fold in the first bending mode and the average change in other modes was between five and 10-fold. The mode shapes of ballasted sleepers were quite difficult to identify since some mode shapes were sometimes too closely spaced between each mode of vibration. The effect of boundary conditions on vibration properties of sleepers is depicted in Figure 5. Apparently, the voids and pockets tend to have higher influence on modal results corresponding to the flexural modes of vibration than those associated with the torsional modes. It should be noted that by degrees the dynamic softening phenomenon (natural frequency reduces as the amount of voids increases) prevails when voids and pockets occur.

The experimental modal results for Sleeper No. 2 (AUSTRAK Narrow Gauge) are presented in Table 3. The frequency change between the free-free and full-contact in-situ conditions ranged from approximately 0.3 to 7 percent. The ballast support substantially augmented the damping values of all vibration modes, varying from two to 30 times. The same trends in frequencies and damping constants for the sleepers in free-free and void conditions could be observed in Figure 6. It is the confirmation to the previous test that the dynamic softening phenomenon occurs as the voids and pockets begin. The degree of softening behaviour depends largely on the type of sleepers.

5. CONCLUSIONS

Vibration characteristics of railway concrete sleepers are crucial for the development of a realistic dynamic model of railway track as well as the concrete sleeper itself, which are capable of predicting its dynamic responses. The results of the experimental modal analysis for prestressed concrete sleepers under different boundary conditions are presented in this paper. Two types of prestressed concrete sleepers manufactured in Australia were tested using an impact hammer excitation technique over the frequency range of interest: from 0 to 1600 Hz. The imperfections of contact between ballast and sleeper were artificially constructed, in order to evaluate the influence of voids and pockets on the dynamic properties of the railway sleepers. It was found that the resonant frequencies and damping ratios associated with the lower mode of vibration of prestressed concrete sleepers were considerably affected by the support boundary conditions, including the voids and pockets. However, the influence of the voids and pockets was reduced in the higher frequency range, particularly in torsional modes of vibration. The voids and pockets are likely to interact more with the flexural modes of vibration rather than the torsional modes. The dominant effect of the ballast support was placed on the modal damping in the ballast-sleeper interaction. In addition, the mode shapes, which can indicate the deteriorated state of concrete sleepers, were affected by the ballast conditions. In summary, the void and pocket condition had a remarkable influence on the natural frequency, modal damping, and vibration mode shape of prestressed concrete sleepers, especially in the low frequency range and flexural deformation. It is recommended that the determined parameters of concrete sleepers associated with the voids and pockets be used in modelling of railway tracks where the effect of the ballast degradation will be taken into account.

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